PROCEEDINGS OF SCIENCE

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Galactic Gamma-Ray Diffuse Emission at TeV energies with HAWC Data

Amid Nayerhoda,[a,*] F. Salesa Greus,[a] S. Casanova,[a,b] D. Grasso,[c] A. Marinelli,[d] D. Gaggero,[e] S. Ventura[f] and O. Fornieri[c,e,g] on behalf of the HAWC Collaboration
(a complete list of authors can be found at the end of the proceedings)

[a] *Institute of Nuclear Physics, Polish Academy of Sciences*
ul. Radzikowskiego 152, 31-342 Krakow, Poland
[b] *Max-Planck Institute for Nuclear Physics,*
Heidelberg, Germany
[c] *INFN, Sezione di Pisa, Polo Fibonacci,*
Largo B. Pontecorvo 3, 56127 Pisa, Italy
[d] *INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo,*
Via Cintia ed. G, 80126 Napoli, Italy
[e] *Instituto de Física Teórica UAM-CSIC, Campus de Cantoblanco,*
E-28049 Madrid, Spain
[f] *University of Siena and INFN Pisa,*
via Roma 56, 57100 Siena - Italy
[g] *Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente, Università di Siena,*
Via Roma 56, 53100 Siena, Italy
E-mail: Amid.nayerhoda@ifj.edu.pl

The Galactic gamma-ray diffuse emission is produced by the interaction of cosmic rays with ambient gas and electromagnetic radiation fields in the interstellar medium (ISM). Studying this radiation helps reconstruct the particle transport mechanisms and the particle distribution in the Galaxy. In this work, we analyze the TeV diffuse emission in a chosen region of the Galactic plane using data collected with the High Altitude Water Cherenkov (HAWC) detector. The energy and spatial distributions of the diffuse Galactic gamma-ray radiation have been studied after subtracting extended and point sources detected with greater than 5 sigma significance from the region map. The spectral feature of the aforementioned emission is compatible with the gamma-ray emissivity obtained from the locally measured proton and heavier nuclei spectrum, convolved with the gas distribution in the Galaxy.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

PoS(ICRC2021)835

1. Introduction

The Galactic gamma-ray diffuse emission is the radiation produced by the highly energetic hadrons and electrons, known as cosmic rays (CRs), when these particles interact with the interstellar medium (ISM) gas and radiation field (ISRF). CR hadrons collide with the ambient gas atoms and molecules and produce gamma-rays through neutral pion (π^0) decay. CR electrons emit gammas via inverse Compton (IC) scattering off the cosmic microwave background (CMB) and ISRF photons. The Galactic gamma-ray emission is a proxy of the parental CR population.

Due to their charged nature, after escaping their acceleration sources the particles diffuse in the Galactic electromagnetic fields. Cosmic rays, which have left long ago their acceleration sources and have already undergone a spectral softening due to diffusion, are known collectively as CR sea or background cosmic rays. Background CRs produce the diffuse emission.

Until recently, the CR energy spectrum measured close to Earth followed a simple-power law (SPL) below 1 PeV, with a spectral index between -2.7 and -2.8. Recently, PAMELA, AMS, and CREAM [5, 18] detected a hardening in the spectra of CR proton, helium, and other primary nuclear species. The spectra at about 300 GeV/n (GeV per nucleon) has a spectral index close to -2.6 [15]. The origin of the hardening is not clear. It is also not clear whether the hardening is a local effect ([16]), and whether it continues beyond several TeV in energy. More generally, it is not clear whether the spectrum of the CR sea is the same everywhere in the Galaxy or it hardens towards the inner Galaxy [12, 13].

The contribution of source emission to the TeV radiation is presently another highly debated topic. While the GeV radiation from the Galactic Plane is predominantly due to the interaction of background CRs, the Galactic Plane radiation at TeV energies is expected to be dominated by source emissions. Thus at TeV energies the diffuse emission from background CRs should be faint and difficult to detect [10]. However, recent measurements by Tibet Array [6] point to a significant genuine diffuse component to the Galactic Plane radiation at hundred TeVs. Studying the GDE helps to reconstruct the distribution of background CRs in the Galaxy and solve the open questions concerning the spectrum of the CR sea.

The High Altitude Water Cherenkov Gamma-Ray Observatory[1], located on the Sierra Negra volcano near Puebla, Mexico, at an altitude of 4,100 meters, is an extensive air shower array designed to observe gamma rays and CRs between 300 GeV to above 100 TeV [1].

We here present the GDE measurements by HAWC from a region of the Galactic Plane extended over $l \in [43°, 73°]$ in longitude and $b \in [-5°, 5°]$ in latitude. This is referred to as the region of interest (ROI). Finally, we discuss briefly our observational results.

2. Analysis

2.1 Data-set, Event and Background Maps

The data set used for GDE analysis presented in this study has been collected over 1,347 days by HAWC detector from 2013 to 2019. In HAWC the events are divided into nine bins, related to the size of the event on the HAWC array, the size of the event being a proxy of the energy of the event. By considering all bins, we include gamma-rays with energies from 300 GeV to 100 TeV [1].

[1]https://www.hawc-observatory.org/

On one hand the emission from gamma-ray sources is mostly located on the Galactic Plane. On the other hand the emission produced by diffusing background CRs (the GDE) is expected to extend beyond 1-2 degrees below and above the Galactic Plane. Since the goal of our analysis is the study of the GDE, we choose a ROI with latitudinal range $b \in [-5°, 5°]$, which encompasses extended regions outside the Galactic Plane.

The HAWC data analysis is based on the generation of maps of the events and background. The background is estimated with a method known as "direct integration" [8]. The event maps are histograms of the reconstructed events (Data = signal + background) that pass gamma/hadron cuts [2]. The maps used in this analysis are generated using HEALPix pixelization [14] with Nside = 1024.

2.2 Analysis of the GDE

The total flux measured by HAWC from the Galactic Plane is the sum of source emission, including point-like and extended sources, and diffuse radiation:

$$F_{\rm tot} = F_{\rm sources} + F_{\rm GDE} \tag{1}$$

The significance map[2] of the total radiation measured by HAWC is shown[3] in Figure 1 (hereafter called "original map").

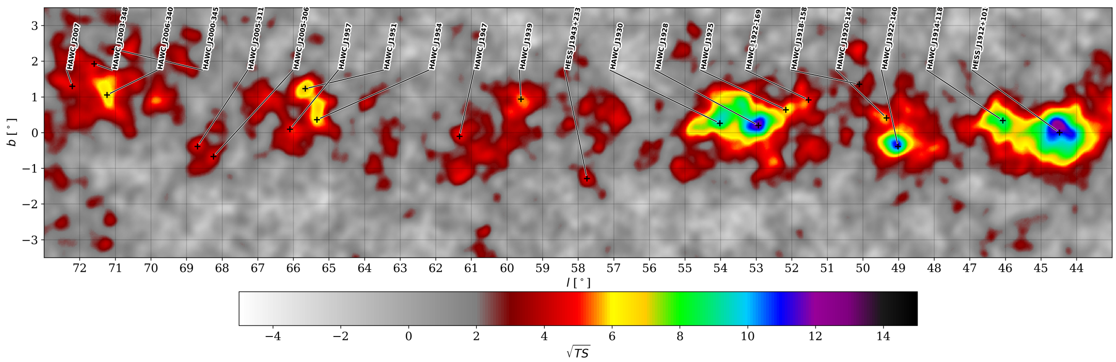

Figure 1: Significance map of the total gamma-ray radiation within the ROI.

The first step of the GDE analysis takes the total gamma-ray radiation measured by HAWC and separates the emission due to the sources from the emission due to the GDE by subtracting the source emission from the original map in Figure 1. In order to obtain the source emission map we fit the total HAWC radiation to a model including GDE and gamma-ray sources. The model includes 21 extended or point-like sources resolved with HAWC (Figure 2 top), and a morphological template of the GDE. The spectral parameters of the point-like and extended sources are assumed to be SPL. Extended sources in the model have a Gaussian morphology with variable size. The normalized 2-D template carrying the morphology of the GDE is obtained with the `DRAGON` code

[2]A significance map is a 2-D visualization of the significance value per pixel, where significance = $\sqrt{TS}$.

[3]All significance maps are created assuming an SPL with a spectral index of -2.7.

([12, 13]). The spectral parameters of all sources and of the GDE and the size of the extended sources are free to be fitted with HAWC data in a multi-source fitting (fitting all the sources and GDE together) procedure.

The best fit of the GDE and all sources is computed with a likelihood method[4]. Test statistics (TS), residual maps, and significance histograms are considered to choose the preferred models.

The obtained source-subtracted map is shown in (Figure 3). The final step of the analysis consists in obtaining the spectral parameters of the GDE emission from this source-subtracted map or GDE map.

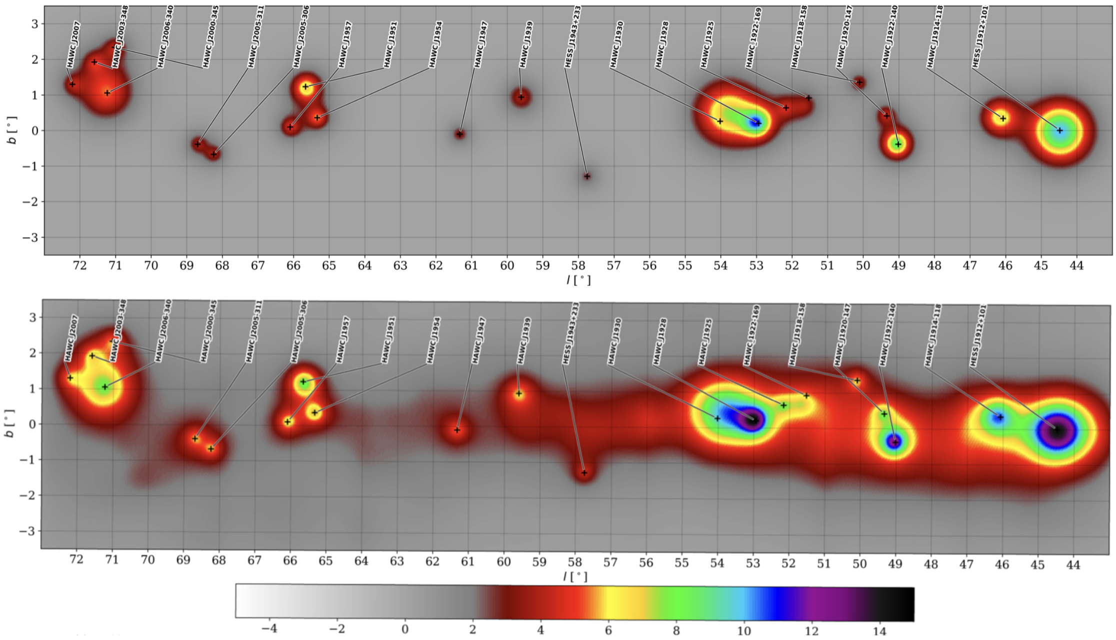

Figure 2: Top: the significance map for the model of all sources (point-like and extended source). Bottom: significance map of the fitted model for all sources and GDE.

3. Results

The results of the measurements of the GDE distribution with HAWC data are reported in Table 1. The contribution of the GDE flux to the total emission is calculated in 2 energy ranges; between 300 GeV and 10 TeV, and between 300 GeV and 100 TeV, that are shown as f10 and f100 respectively [(F_{GDE}) / (F_{tot})]. The contribution of the diffuse emission to the total gamma-ray radiation from the Galactic Plane varies between 71.8% and 76.1% in different sub-regions (see Table 1) [7]. Assuming that the spectrum of the diffuse emission is described as in energy, its spectral index is -2.61 ± 0.03 (see table 1).

[4]The Multi-Mission Maximum Likelihood (3ML) framework [17] is used for the likelihood analysis.

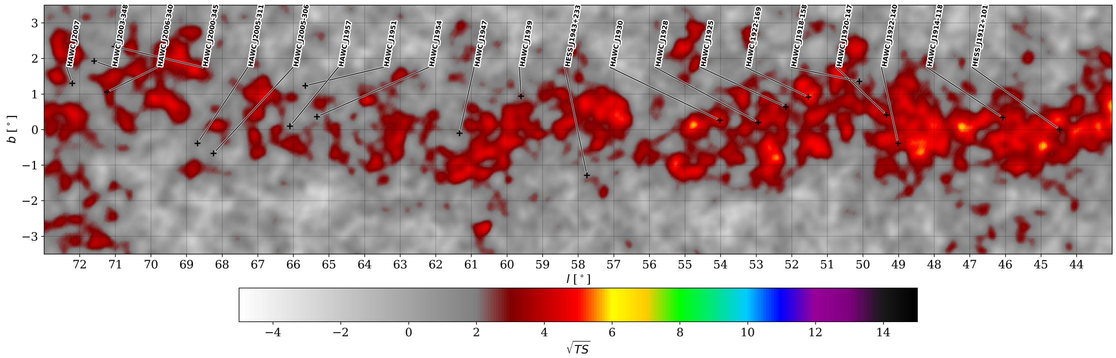

Figure 3: The significance map of the GDE map produced by subtracting the model of the sources from the original map.

l_{min} (°)	l_{max} (°)	$>\|b\|$ (°)	Normalization (7.0 TeV)	Normalization Error (7.0 TeV)	Index	Index Error	f10 %	f100 %
43	73	2	8.89	$0.37^{-0.70}_{+0.48}$	-2.612	$0.030^{-0.036}_{+0.015}$	72.7	71.8
43	73	4	5.45	$0.25^{-0.44}_{+0.38}$	-2.604	$0.034^{-0.037}_{+0.012}$	76.1	75.3

Table 1: Spectrum of the GDE within the ROI for $|b|<2°$ and $|b|<4°$. f10 and f100 are the fraction of the GDE flux with respect to the total HAWC flux, up to 10 TeV and 100 TeV respectively. Normalization: ($10^{-12} \times$ TeV $s^{-1}cm^{-2}sr^{-1}$). The first error shows the statistical, and the second presents the systematic uncertainty.

4. Discussion and conclusions

We presented the spatial and spectral parameters of the GDE measured by HAWC within a region of the Galactic Plane extended over ($l \in [43°, 73°]$ and $b \in [-5°, 5°]$) for energies above 300 GeV and up to 100 TeV. The spectrum of the diffuse emission can be described as a power law with spectral index, -2.61 ± 0.03 (see table 1). From the gamma-ray spectrum we can deduce the parental CR spectrum in the analysed region. Our analysis shows that the CR spectral index is on average compatible with the spectral index of the locally measured CR spectrum. Also, the CR spectral hardening at rigidity around 300 GeV measured by PAMELA and AMS [4] seems not to be a local effect but rather a large-scale feature. Finally, the dominant contribution to the radiation at multi TeV from the Galaxy seems to be diffuse emission, in agreement with recent results by the Tibet Array observatory [7]. Due to the uncertain contribution to the measured emission coming from unresolved sources, the results presented here are a maximum limit for the GDE.

The diffuse emission at TeV energies will be studied with better sensitivity and energy/angular resolution by current and upcoming TeV observatories such as the LHAASO [9], the SWGO Observatory [3], and the Cherenkov Telescope Array [11].

Acknowledgments

We acknowledge the support from: the US National Science Foundation (NSF); the US Department of Energy Office of High-Energy Physics; the Laboratory Directed Research and Development (LDRD) program of Los Alamos National Laboratory; Consejo Nacional de Ciencia y Tecnología (CONACyT), México, grants 271051, 232656, 260378, 179588, 254964, 258865, 243290, 132197, A1-S-46288, A1-S-22784, cátedras 873, 1563, 341, 323, Red HAWC, México; DGAPA-UNAM grants IG101320, IN111716-3, IN111419, IA102019, IN110621, IN110521; VIEP-BUAP; PIFI 2012, 2013, PROFOCIE 2014, 2015; the University of Wisconsin Alumni Research Foundation; the Institute of Geophysics, Planetary Physics, and Signatures at Los Alamos National Laboratory; Polish Science Centre grant, DEC-2017/27/B/ST9/02272; Coordinación de la Investigación Científica de la Universidad Michoacana; Royal Society - Newton Advanced Fellowship 180385; Generalitat Valenciana, grant CIDEGENT/2018/034; Chulalongkorn University's CUniverse (CUAASC) grant; Coordinación General Académica e Innovación (CGAI-UdeG), PRODEP-SEP UDG-CA-499; Institute of Cosmic Ray Research (ICRR), University of Tokyo, H.F. acknowledges support by NASA under award number 80GSFC21M0002. We also acknowledge the significant contributions over many years of Stefan Westerhoff, Gaurang Yodh and Arnulfo Zepeda Dominguez, all deceased members of the HAWC collaboration. Thanks to Scott Delay, Luciano Díaz and Eduardo Murrieta for technical support.

References

[1] Abeysekara, A. U., Albert, A., Alfaro, R., et al. 2017, The Astrophysical Journal, 843, 39, doi: 10.3847/1538-4357/aa7555

[2] Abeysekara, A. U., Albert, A., Alfaro, R., et al. 2017, Astrophysical Journal, 843, 40, doi: 10.3847/1538-4357/aa7556

[3] Abreu, P., Albert, A., Alfaro, R., et al. 2019, The Southern Wide-Field Gamma-Ray Observatory (SWGO): A Next-Generation Ground-Based Survey Instrument for VHE Gamma-Ray Astronomy. https://arxiv.org/abs/1907.07737

[4] Aguilar, M., et al. 2018, Phys. Rev. Lett., 120, 021101, doi: 10.1103/PhysRevLett.120.021101

[5] Ahn, H. S., et al. 2010, Astrophys. J., 714, L89, doi: 10.1088/2041-8205/714/1/L89

[6] Amenomori, M., Bao, Y. W., Bi, X. J., et al. 2021, Phys. Rev. Lett., 126, 141101, doi: 10.1103/PhysRevLett.126.141101

[7] Amenomori, M. e. a. 2021, Phys. Rev. Lett., 126, 141101, doi: 10.1103/PhysRevLett.126.141101

[8] Atkins, R., Benbow, W., Berley, D., et al. 2003, The Astrophysical Journal, 595, 803, doi: 10.1086/377498

[9] Bai, X., Bi, B. Y., Bi, X. J., et al. 2019, The Large High Altitude Air Shower Observatory (LHAASO) Science White Paper. https://arxiv.org/abs/1905.02773

[10] Casanova, S., & Dingus, B. L. 2008, Astroparticle Physics, 29, 63, doi: 10.1016/j.astropartphys.2007.11.008

[11] Consortium, T. C. T. A., :, Acharya, B. S., et al. 2017, Science with the Cherenkov Telescope Array. https://arxiv.org/abs/1709.07997

[12] Evoli, C., Gaggero, D., Grasso, D., & Maccione, L. 2008, Journal of Cosmology and Astroparticle Physics, 2008, 018, doi: 10.1088/1475-7516/2008/10/018

PoS(ICRC2021)835

[13] Evoli, C., Gaggero, D., Vittino, A., et al. 2017, Journal of Cosmology and Astroparticle Physics, 2017, 015, doi: 10.1088/1475-7516/2017/02/015

[14] Hanisch, R. J., Farris, A., Greisen, E. W., et al. 2001, Astronomy and Astrophysics, 376, 359, doi: 10.1051/0004-6361:20010923

[15] Lipari, P. 2018, Astropart. Phys., 97, 197, doi: 10.1016/j.astropartphys.2017.11.008

[16] Thoudam, S., & Horandel, J. R. 2012, Mon. Not. Roy. Astron. Soc., 421, 1209, doi: 10.1111/j.1365-2966.2011.20385.x

[17] Vianello, G., Lauer, R. J., Younk, P., et al. 2015, The Multi-Mission Maximum Likelihood framework (3ML). https://arxiv.org/abs/1507.08343

[18] Yoon, Y. S., Anderson, T., Barrau, A., et al. 2017, The Astrophysical Journal, 839, 5, doi: 10.3847/1538-4357/aa68e4

[a4paper,11pt]article pos

Full Authors List: HAWC Collaboration

A.U. Abeysekara[48], A. Albert[21], R. Alfaro[14], C. Alvarez[41], J.D. Álvarez[40], J.R. Angeles Camacho[14], J.C. Arteaga-Velázquez[40], K. P. Arunbabu[17], D. Avila Rojas[14], H.A. Ayala Solares[28], R. Babu[25], V. Baghmanyan[15], A.S. Barber[48], J. Becerra Gonzalez[11], E. Belmont-Moreno[14], S.Y. BenZvi[29], D. Berley[39], C. Brisbois[39], K.S. Caballero-Mora[41], T. Capistrán[12], A. Carramiñana[18], S. Casanova[15], O. Chaparro-Amaro[3], U. Cotti[40], J. Cotzomi[8], S. Coutiño de León[18], E. De la Fuente[46], C. de León[40], L. Diaz-Cruz[8], R. Diaz Hernandez[18], J.C. Díaz-Vélez[46], B.L. Dingus[21], M. Durocher[21], M.A. DuVernois[45], R.W. Ellsworth[39], K. Engel[39], C. Espinoza[14], K.L. Fan[39], K. Fang[45], M. Fernández Alonso[28], B. Fick[25], H. Fleischhack[51,11,52], J.L. Flores[46], N.I. Fraija[12], D. Garcia[14], J.A. García-González[20], J. L. García-Luna[46], G. García-Torales[46], F. Garfias[12], G. Giacinti[22], H. Goksu[22], M.M. González[12], J.A. Goodman[39], J.P. Harding[21], S. Hernandez[14], I. Herzog[25], J. Hinton[22], B. Hona[48], D. Huang[25], F. Hueyotl-Zahuantitla[41], C.M. Hui[23], B. Humensky[39], P. Hüntemeyer[25], A. Iriarte[12], A. Jardin-Blicq[22,49,50], H. Jhee[43], V. Joshi[7], D. Kieda[48], G J. Kunde[21], S. Kunwar[22], A. Lara[17], J. Lee[43], W.H. Lee[12], D. Lennarz[9], H. León Vargas[14], J. Linnemann[24], A.L. Longinotti[12], R. López-Coto[19], G. Luis-Raya[44], J. Lundeen[24], K. Malone[21], V. Marandon[22], O. Martinez[8], I. Martinez-Castellanos[39], H. Martínez-Huerta[38], J. Martínez-Castro[3], J.A.J. Matthews[42], J. McEnery[11], P. Miranda-Romagnoli[34], J.A. Morales-Soto[40], E. Moreno[8], M. Mostafá[28], A. Nayerhoda[15], L. Nellen[13], M. Newbold[48], M.U. Nisa[24], R. Noriega-Papaqui[34], L. Olivera-Nieto[22], N. Omodei[32], A. Peisker[24], Y. Pérez Araujo[12], E.G. Pérez-Pérez[44], C.D. Rho[43], C. Rivière[39], D. Rosa-Gonzalez[18], E. Ruiz-Velasco[22], J. Ryan[26], H. Salazar[8], F. Salesa Greus[15,53], A. Sandoval[14], M. Schneider[39], H. Schoorlemmer[22], J. Serna-Franco[14], G. Sinnis[21], A.J. Smith[39], R.W. Springer[48], P. Surajbali[22], I. Taboada[9], M. Tanner[28], K. Tollefson[24], I. Torres[18], R. Torres-Escobedo[30], R. Turner[25], F. Ureña-Mena[18], L. Villaseñor[8], X. Wang[25], I.J. Watson[43], T. Weisgarber[45], F. Werner[22], E. Willox[39], J. Wood[23], G.B. Yodh[35], A. Zepeda[4], H. Zhou[30]

[1]Barnard College, New York, NY, USA, [2]Department of Chemistry and Physics, California University of Pennsylvania, California, PA, USA, [3]Centro de Investigación en Computación, Instituto Politécnico Nacional, Ciudad de México, México, [4]Physics Department, Centro de Investigación y de Estudios Avanzados del IPN, Ciudad de México, México, [5]Colorado State University, Physics Dept., Fort Collins, CO, USA, [6]DCI-UDG, Leon, Gto, México, [7]Erlangen Centre for Astroparticle Physics, Friedrich Alexander Universität, Erlangen, BY, Germany, [8]Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla, Puebla, México, [9]School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA, USA, [10]School of Physics Astronomy and Computational Sciences, George Mason University, Fairfax, VA, USA, [11]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [12]Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de México, México, [13]Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Ciudad de México, México, [14]Instituto de Física, Universidad Nacional Autónoma de México, Ciudad de México, México, [15]Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland, [16]Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, SP, Brasil, [17]Instituto de Geofísica, Universidad Nacional Autónoma de México, Ciudad de México, México, [18]Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla, Puebla, México, [19]INFN Padova, Padova, Italy, [20]Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, Ave. Eugenio Garza Sada 2501, Monterrey, N.L., 64849, México, [21]Physics Division, Los Alamos National Laboratory, Los Alamos, NM, USA, [22]Max-Planck Institute for Nuclear Physics, Heidelberg, Germany, [23]NASA Marshall Space Flight Center, Astrophysics Office, Huntsville, AL, USA, [24]Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA, [25]Department of Physics, Michigan Technological University, Houghton, MI, USA, [26]Space Science Center, University of New Hampshire, Durham, NH, USA, [27]The Ohio State University at Lima, Lima, OH, USA, [28]Department of Physics, Pennsylvania State University, University Park, PA, USA, [29]Department of Physics and Astronomy, University of Rochester, Rochester, NY, USA, [30]Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China, [31]Sungkyunkwan University, Gyeonggi, Rep. of Korea, [32]Stanford University, Stanford, CA, USA, [33]Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL, USA, [34]Universidad Autónoma del Estado de Hidalgo, Pachuca, Hgo., México, [35]Department of Physics and Astronomy, University of California, Irvine, Irvine, CA, USA, [36]Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, Santa Cruz, CA, USA, [37]Universidad de Costa Rica, San José , Costa Rica, [38]Department of Physics and Mathematics, Universidad de Monterrey, San Pedro Garza García, N.L., México, [39]Department of Physics, University of Maryland, College Park, MD, USA, [40]Instituto de Física y Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México, [41]FCFM-MCTP, Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, Chiapas, México, [42]Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA, [43]University of Seoul, Seoul, Rep. of Korea, [44]Universidad Politécnica de Pachuca, Pachuca, Hgo, México, [45]Department of Physics, University of Wisconsin-Madison, Madison, WI, USA, [46]CUCEI, CUCEA, Universidad de Guadalajara, Guadalajara, Jalisco, México, [47]Universität Würzburg, Institute for Theoretical Physics and Astrophysics, Würzburg, Germany, [48]Department of Physics and Astronomy, University of Utah, Salt Lake City, UT, USA, [49]Department of Physics, Faculty of Science, Chulalongkorn University, Pathumwan, Bangkok 10330, Thailand, [50]National Astronomical Research Institute of Thailand (Public Organization), Don Kaeo, MaeRim, Chiang Mai 50180, Thailand, [51]Department of Physics, Catholic University of America, Washington, DC, USA, [52]Center for Research and Exploration in Space Science and Technology, NASA/GSFC, Greenbelt, MD, USA, [53]Instituto de Física Corpuscular, CSIC, Universitat de València, Paterna, Valencia, Spain